Spillway Pier Seismic Failure Mechanisms

Best Practices in Dam and Levee Safety Risk Analyses

Part E – Concrete Structures

Chapter E-6

June 2017

US Army Corps of Engineers®

U.S. Department of the Interior Bureau of Reclamation

Department of Energy Federal Energy Regulatory Commission

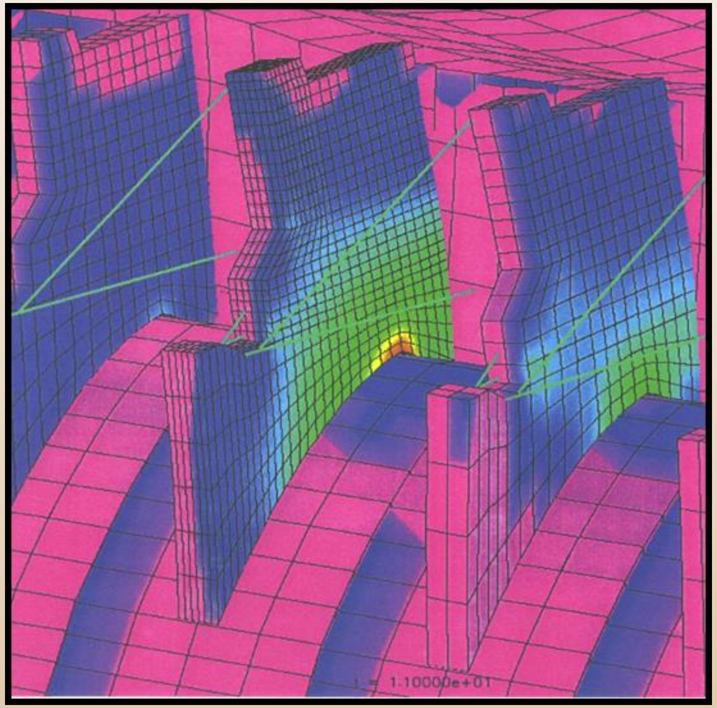
TVA

Outline

- Objectives
- Key Concepts
- Event Tree and Failure Progression
- Other Failure Modes Related to Piers
- Factors influencing strength and stability of reinforced concrete sections
- Analysis for Screening
- Finite Element Analysis
- Limited Case History
- Example

Objectives

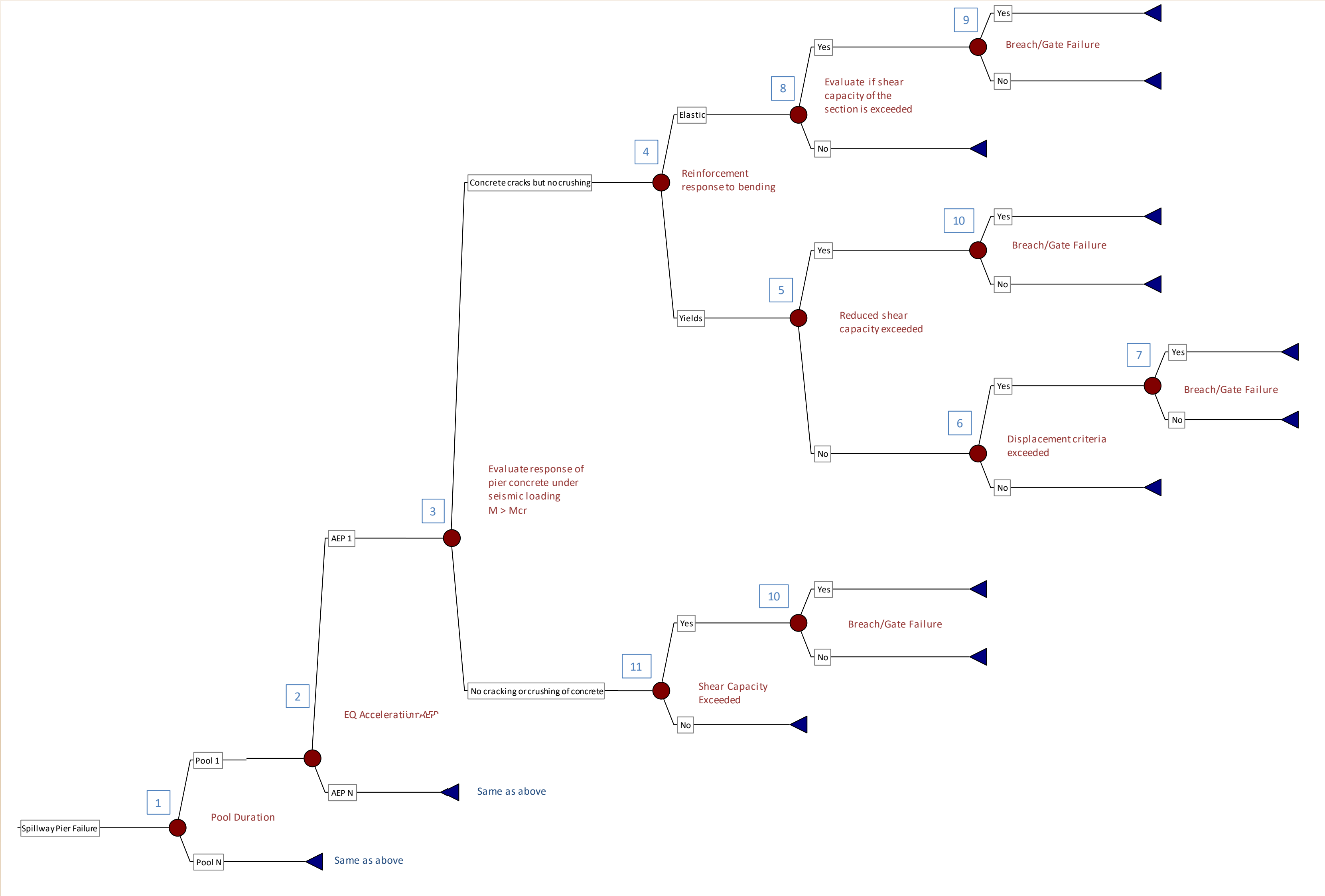
- Understand failure mechanism for piers subjected to seismic loading
- Learn analysis procedures for evaluating a seismic failure of pier
- Failure mode needs to be evaluated since analyses with large earthquake loadings have indicated potential for failure leading to modification at several dams (BOR).



Key Concepts

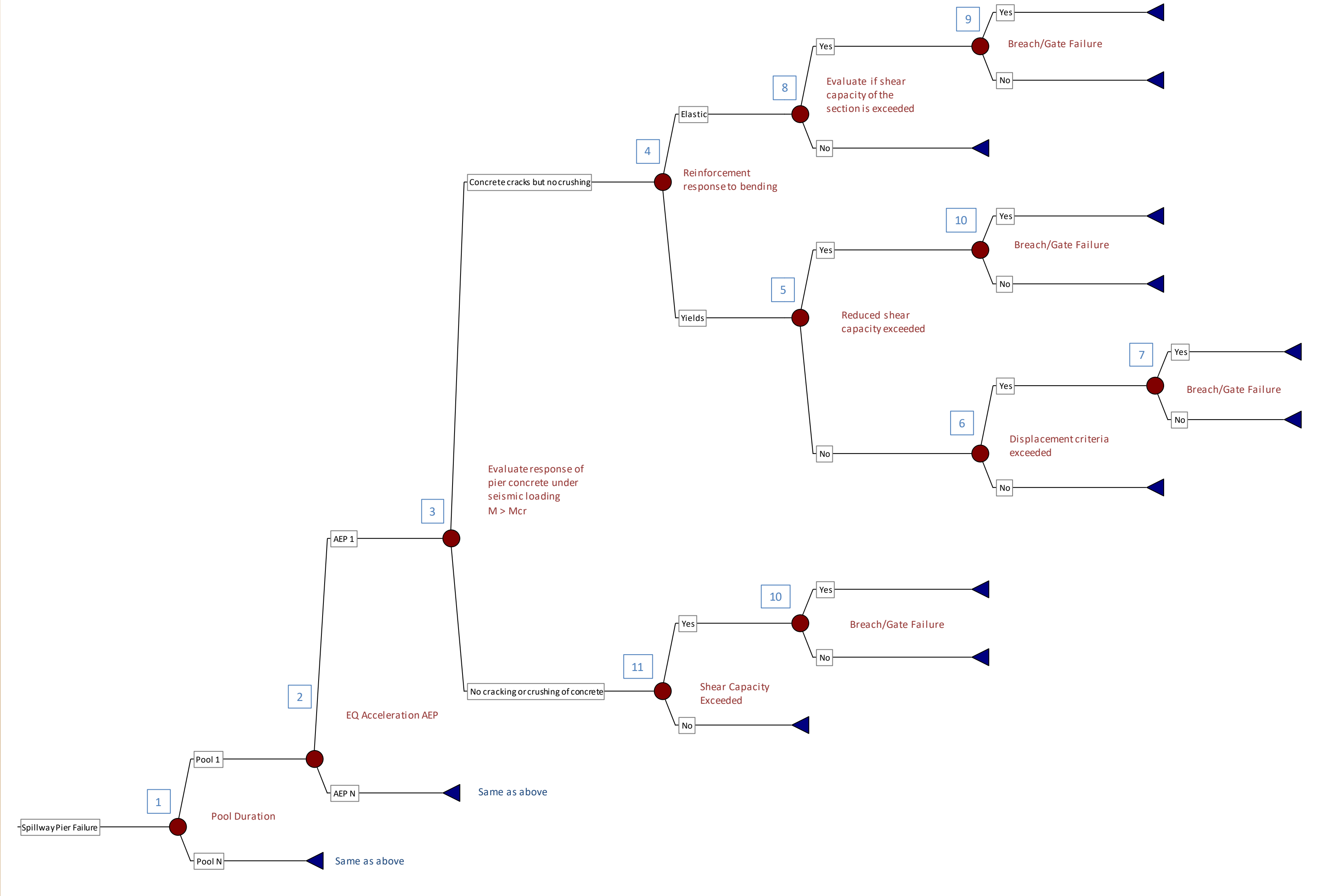
- Reinforced concrete failure mechanisms are well understood and documented
- There have been no known spillway pier failures resulting from seismic shaking.
- Reservoir water level on spillway crest structure is a key parameter for this potential failure mode
- Large hydrodynamic loads can be transferred from gates to piers during an earthquake (static and Hydrodynamic loading).
- Pier geometry affects seismic response; a stiffer pier may attract more load, while a flexible pier may relieve load through deflection
- Loading in cross canyon and US-DS direction.

Event Tree



Spillway Pier Failure
1
Pool Duration
Pool 1
Pool N
Same as above
2
EQ Acceleration-AEP
AEP 1
AEP N
Same as above
3
Evaluate response of pier concrete under seismic loading M > Mcr
Concrete cracks but no crushing
No cracking or crushing of concrete
4
Reinforcement response to bending
Elastic
Yields
8
Evaluate if shear capacity of the section is exceeded
Yes
No
9
Breach/Gate Failure
Yes
No
5
Reduced shear capacity exceeded
Yes
No
10
Breach/Gate Failure
Yes
No
6
Displacement criteria exceeded
Yes
No
7
Breach/Gate Failure
Yes
No
11
Shear Capacity Exceeded
Yes
No
10
Breach/Gate Failure
Yes
No

Event Tree



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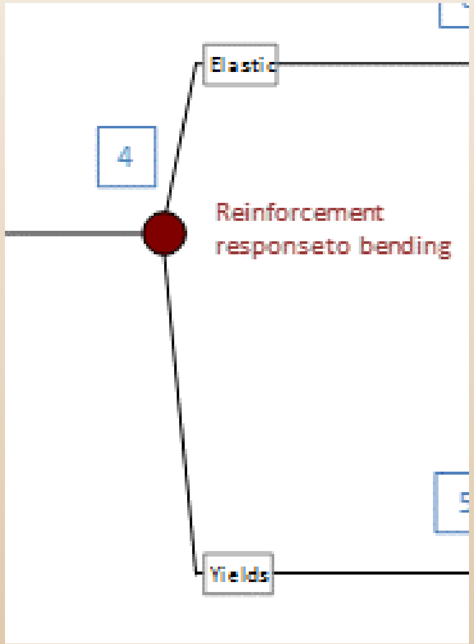
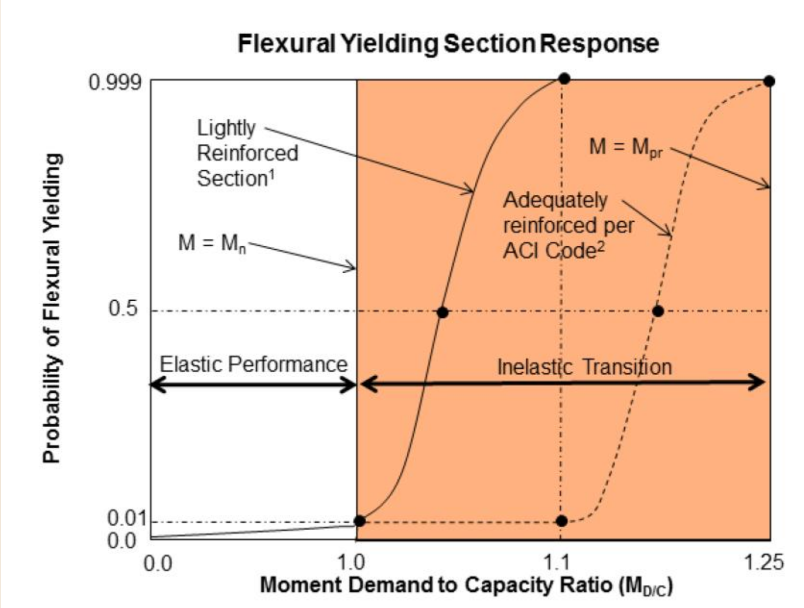
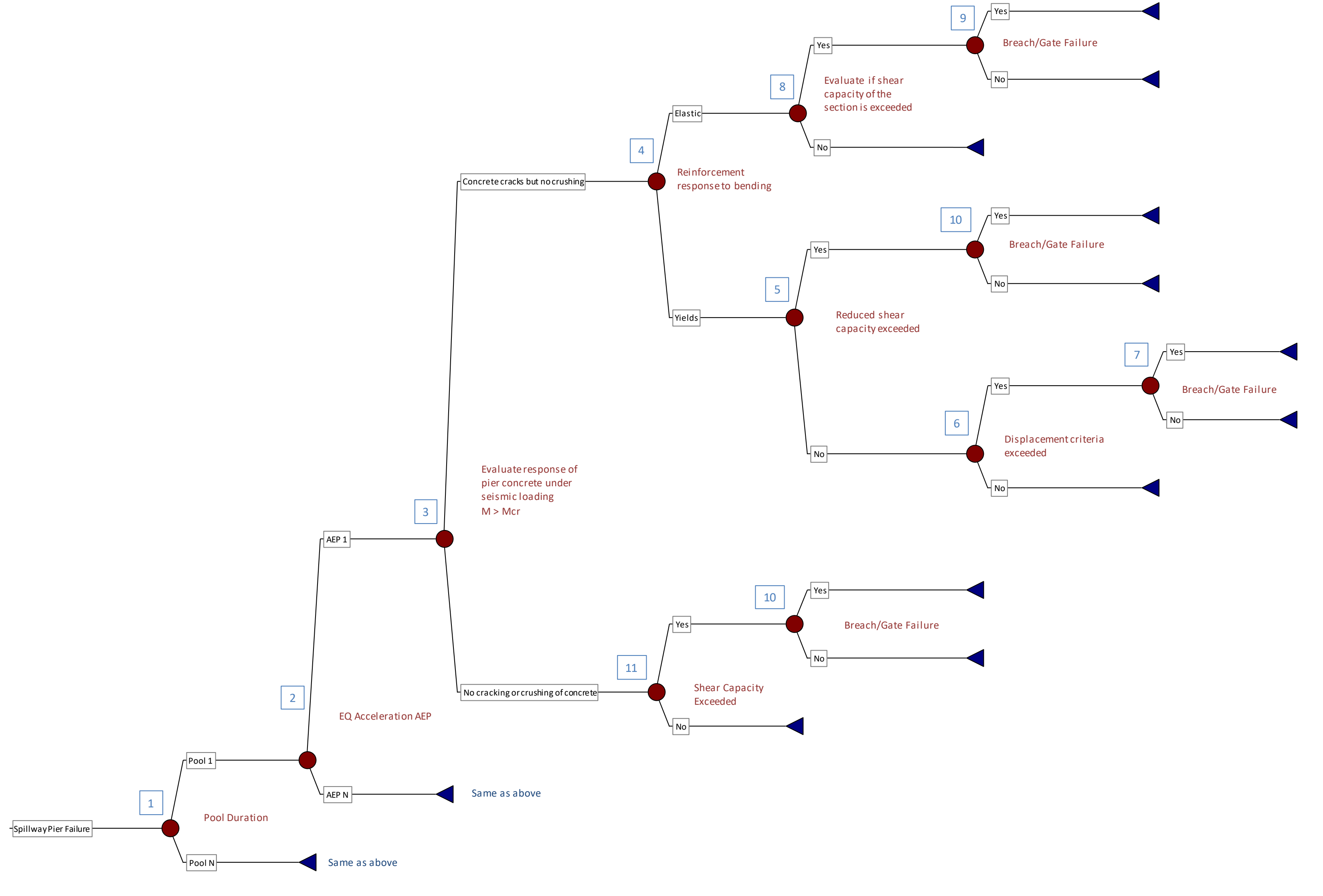
Event Tree

- Can be evaluated with pseudo-static or pseudo dynamic analysis
- Must account for amplification of seismic acceleration
- If concrete cracks and reinforcement yields, evaluate:
    1. Shear capacity in CC and US/DS direction
    2. Displacement criteria that would lead to non-linear deformation or failure of the radial gate
- Use fragility curve to evaluate probability of flexural yielding based on D/C ratio.
- Fragility curves can be created by the team based on the project





Event Tree



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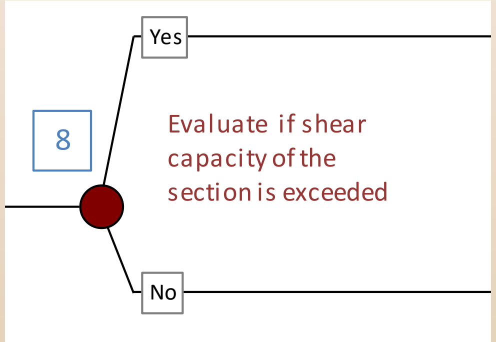
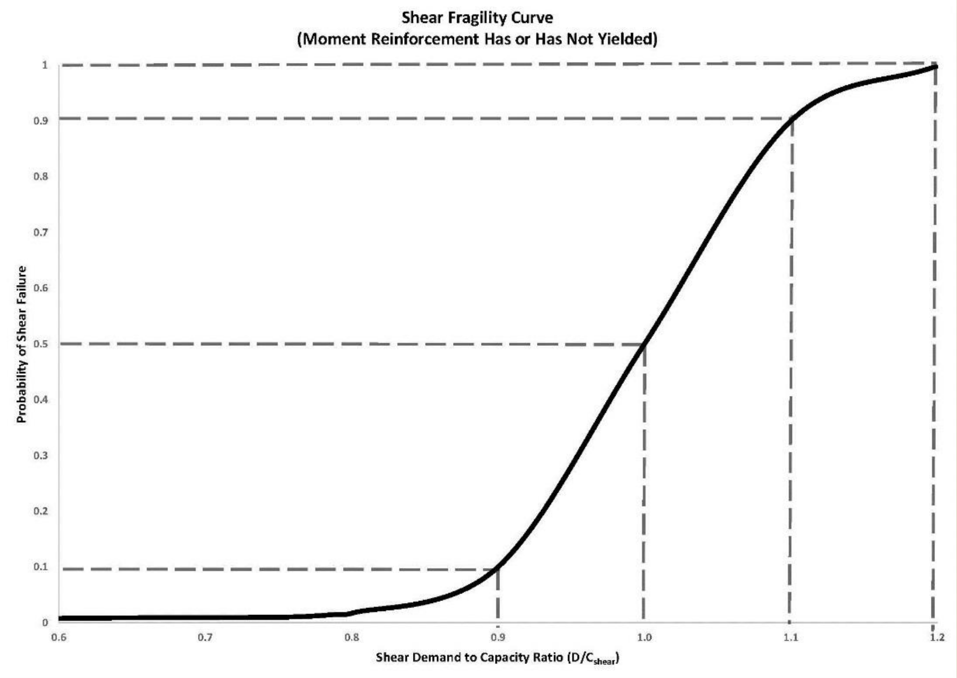
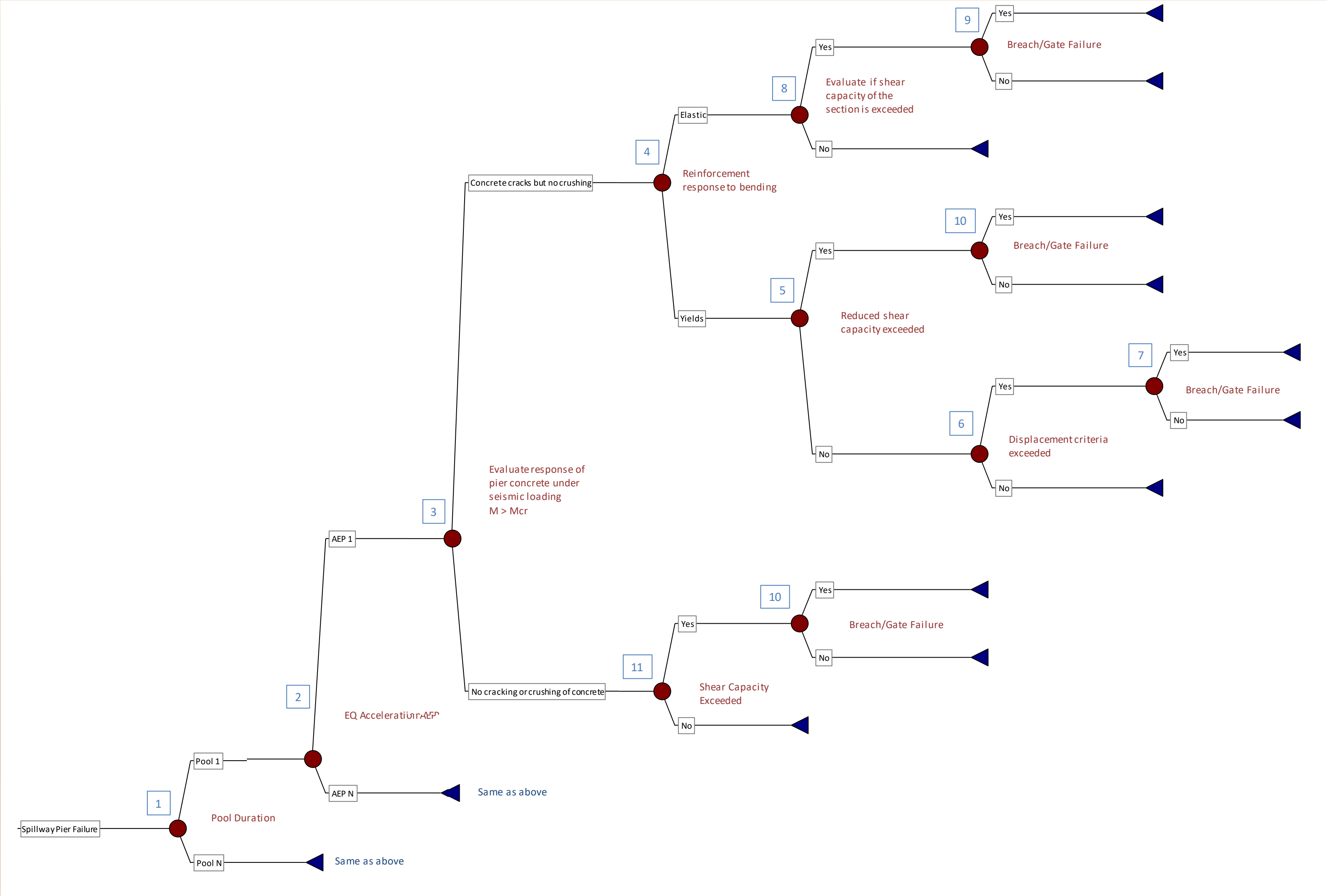
Event Tree

- Evaluate in both the US/DS direction and cross canyon direction.
- Shear strength dependent location in the event tree and whether the concrete has cracked or not.
- Use fragility curve to evaluate probability of shear failure based on D/C ratio.
- Fragility curves can be created by the team based on the project





Event Tree



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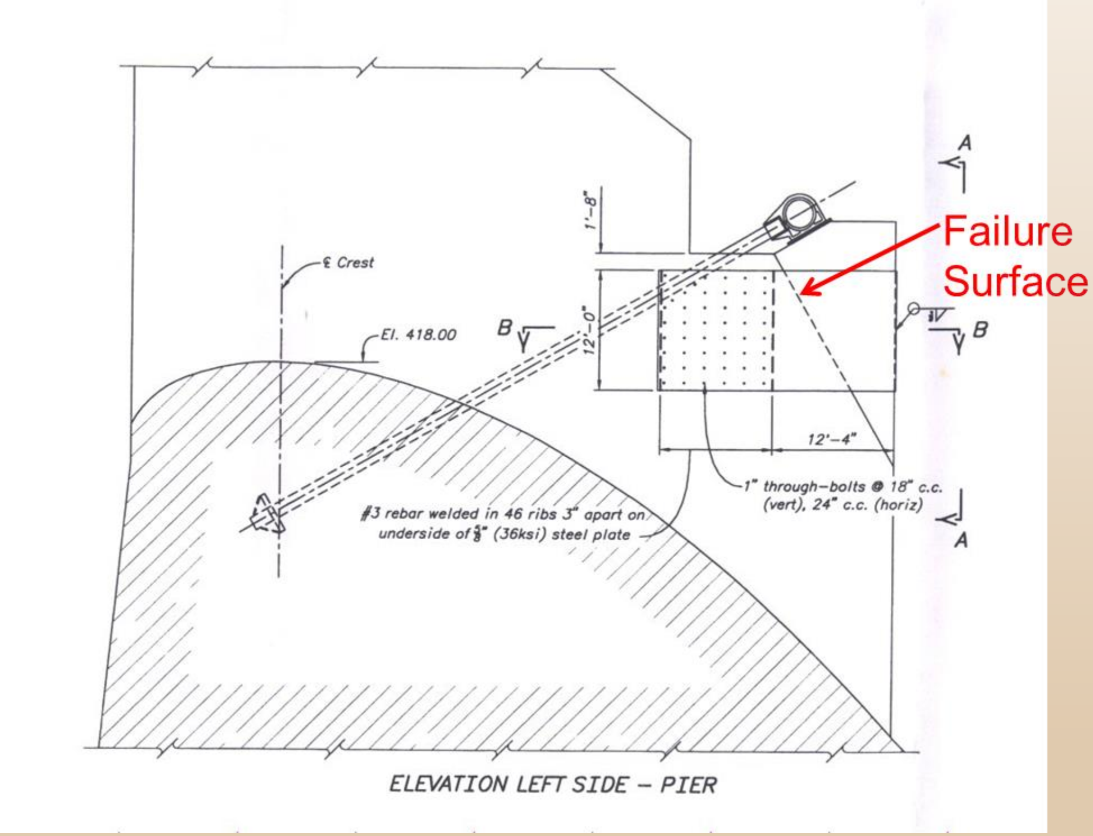
Other Failure Modes Related to Piers

- Failure of the Gate Anchorage or Local Overstressing of Concrete due to loads transmitted from the gates
  - Large hydrodynamic loads can be transferred from gates to piers during an earthquake
  - Anchorage is evaluated for static and hydrodynamic loads on gate – assuming full load is transferred to trunnion and trunnion anchorage
  - A time-history analysis may indicate that anchorage can not strain enough to fail (for anchors with unbonded free length)



Key Factors Influencing PFM Evaluation

- Reservoir Water Surface Elevation
- Pier Geometry
- Moment Capacity
- Shear Capacity
- Seismic Hazard
- Spillway Bridges
- Gate Loads
- Trunnion Anchorage
- Evaluation of Multiple Piers

Reinforced Concrete
Failure Mechanisms

Pier Geometry

- Pier geometry affects seismic response
- Stiffer pier may attract more load, while a flexible pier may relieve load through deflection
- Response depends on frequency of pier and dam, and frequency content of earthquake
- Response depends on whether the crest structure is founded on rock or soil
- Configuration of an abutment slope above the spillway crest structure
- Orientation of the embankment with respect to the spillway crest structure

Moment and Shear Capacity

- Many Reclamation and USACE spillway structures have piers that were not designed for current seismic loads and don't have shear reinforcement.
- Geometry, reinforcement and support conditions of the section
- Material properties of the reinforcement and concrete
- Type and duration of loading
- Loading in each direction (cross-canyon & u/s-d/s)
- Location of the reinforced concrete members relative to the entire structure
- Simple pseudo-static analysis can be used to evaluate moment and shears. Amplification of loading must be considered
- A time history analysis will provide a more complete picture of:
    - the extent of overstressing
    - the number of overstress excursions
- Can model non-linear behavior with finite element modeling

Seismic Hazard

- If reservoir is only up on the gates for limited durations, may be able to make the case that failure probability is remote
- Most spillway piers have some reserve capacity beyond stress levels created by static loads
- Most piers were not designed for significant seismic loading
- Some Reclamation structures currently have PHA for 10,000 year earthquake level of > 1.0g
- Level of seismic loading in combination with static loading will determine level of overstress in pier

The Impact of Spillway Bridges

- Bridges are typically provided across the top of spillway crest structures – hoist decks and highway bridges
- Bridges may serve as struts for piers but this needs to be verified
- Bridges can add inertial loads at top of piers
- Bridges can also fail during an earthquake and possibly impact gates

Gate Loads & Trunnion Anchorage

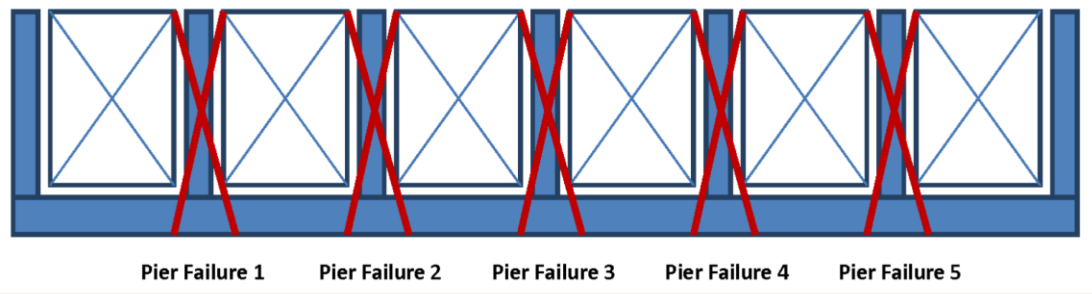
- Large hydrodynamic loads can be transferred from gates to piers during an earthquake
- Anchorage is evaluated for static and hydrodynamic loads on gate – assuming full load is transferred to trunnion and trunnion anchorage
- Current condition of anchorage should be evaluated
- Pseudo-static analysis may indicate that trunnion anchorage is stressed to levels beyond ultimate capacity
- A time-history analysis may indicate that anchorage can not strain enough to fail (for anchors with unbonded free length)
- Loads transmitted from gates into walls can lead to sliding or local overstressing of concrete

Evaluation of Multiple Piers

- Multiple piers increase the probability of pier failure
- Failure of one pier will most likely lead to failure of two gates
- Multiple pier failure will increase the breach outflow and downstream consequences
- If multiple pier failures occur, consequences will be a function of failure configuration (series vs. staggered)

Probability for Single Pier Failure		0.001	0.05	0.16	0.94
No. of Piers Failing	Equation for "x" Piers Failing	Probability for "x" Piers Failing	Probability for "x" Piers Failing	Probability for "x" Piers Failing	Probability for "x" Piers Failing
0	$1P^0(1-P)^5$	0.995	0.774	0.418	7.8E-7
1	$5P^1(1-P)^4$	0.005	0.204	0.398	6.0E-05
2	$10P^2(1-P)^3$	1.0E-05	0.021	0.152	1.9E-03
3	$10P^3(1-P)^2$	1.0E-08	0.001	0.029	0.03
4	$5P^4(1-P)^1$	5.0E-12	3.0E-05	0.003	0.234
5	$1P^5(1-P)^0$	1.0E-15	3.0E-07	1.0E-04	0.734
Total Probability of One or More Piers Failing		0.005	0.226	0.582	1.00

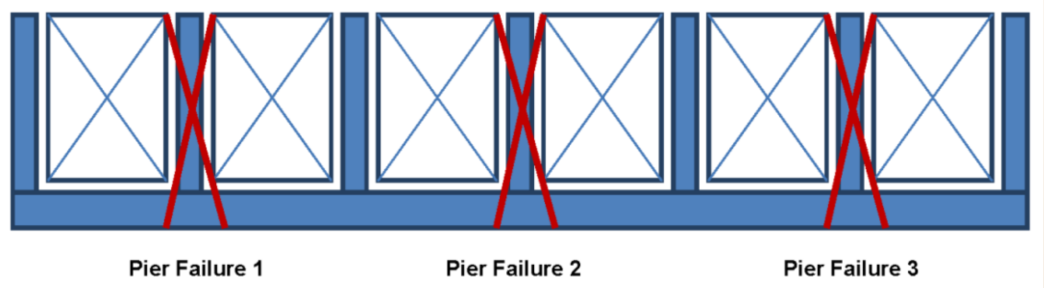
Pier Failure – n+1 (P=0.16) Scenario



Number of Piers Failing	Probability of Failure Equations	Probability (P_x) of (x) Piers Failing	Expected Life Loss Value	Life Loss for (x) Piers Failing x (P_x)
1	$P_1 = 5(P)^1(1\text{-}P)^4$	0.398	16*	6.37
2	$P_2 = 10(P)^2(1\text{-}P)^3$	0.152	23*	3.50
3	$P_3 = 10(P)^3(1\text{-}P)^2$	0.029	30*	0.87
4	$P_4 = 5(P)^4(1\text{-}P)^1$	0.003	147	0.44
5	$P_5 = 1(P)^5(1\text{-}P)^0$	1.0E-04	164	0.02
Totals		**0.58**		**11**

Weighted Ave Loss of Life = 11/0.58 = 19 people

Pier Failure – 2n (P=0.16) Scenario



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2	$P_2 = 10(P)^2(1\text{-}P)^3$	0.152	30*	4.56
3	$P_3 = 10(P)^3(1\text{-}P)^2$	0.029	164	4.76
4	$P_4 = 5(P)^4(1\text{-}P)^1$	0.003	164	0.49
5	$P_5 = 1(P)^5(1\text{-}P)^0$	1.0E-04	164	0.02
Totals		**0.58**		**16**

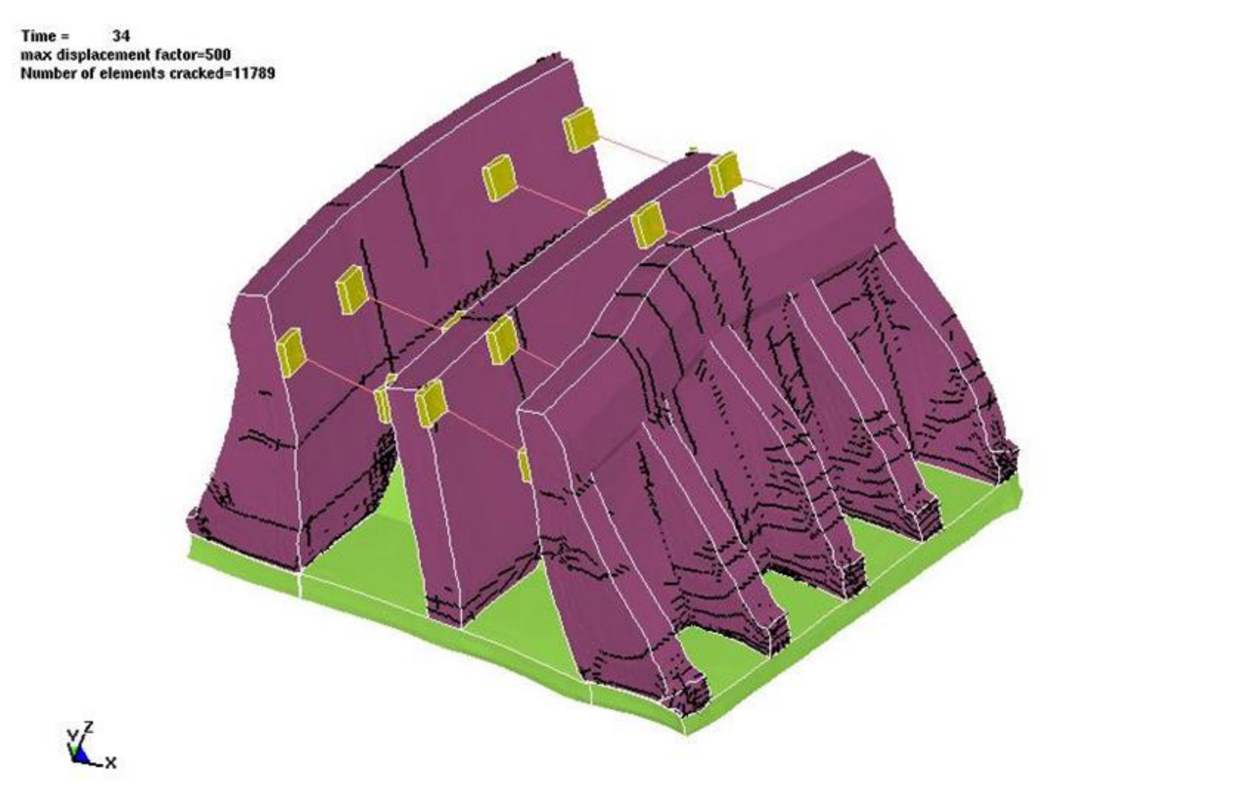
Weighted Ave Loss of Life = 16/0.58 = 28 people

Analysis Methodology for Screening

- If M > Mcr develop a SRP for pool and EQ loading.
- If above TRG then go to more rigorous analysis.
- Pseudo-dynamic analysis of monolith recommended to calculate amplifications at location of failure in US/DS direction.
- Amplification of seismic accelerations of 1.5 in the cross canyon direction assumed.
- Use pseudo-static correction of 2/3.
- FEM should be used for additional analysis due to three dimensionality of loading and structural response.

Finite Element Analysis

- Linear elastic analysis should be done first and may be enough to plot risk below TRG.
- Full nonlinear results – concrete cracking, reinforcing yielding
- Walls and piers crack and are damaged, but remain standing

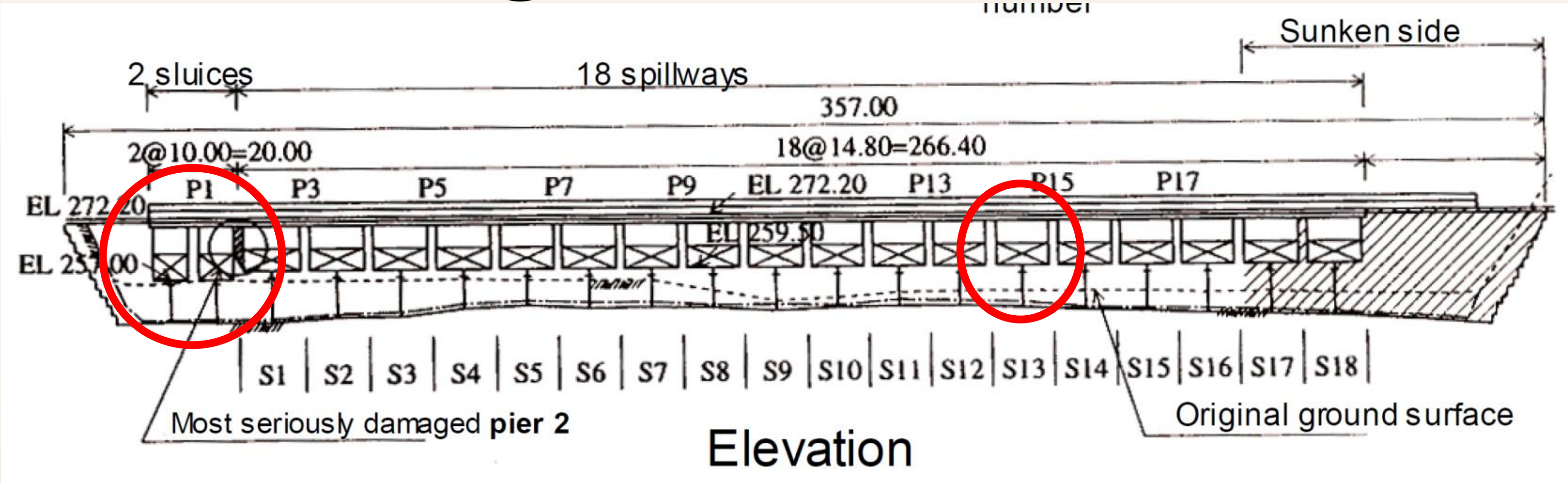


Case History – Shih Kang Dam (Taiwan)

- Gravity Dam with an 18 bay gated spillway
- Located about 30 miles north of the epicenter of the Chi-Chi earthquake (9/21/99)
- Chelungpu fault passed underneath spillway and ruptured during earthquake
- Vertical offset at spillway of 32-36 feet
- PHA – 0.51g recorded 0.3 miles from dam
- But evidence that ground shaking at the site was not that intense

Shih Kang Dam

Shih Kang Dam



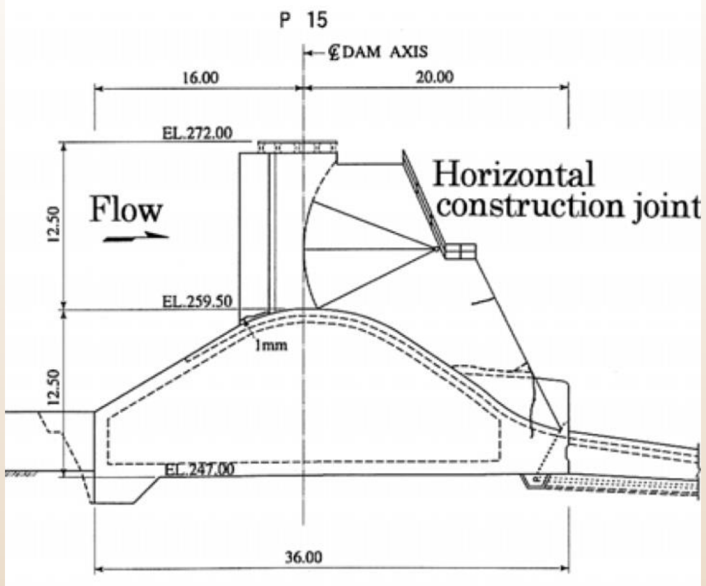


Figure 2.21. Cracks on Pier #14

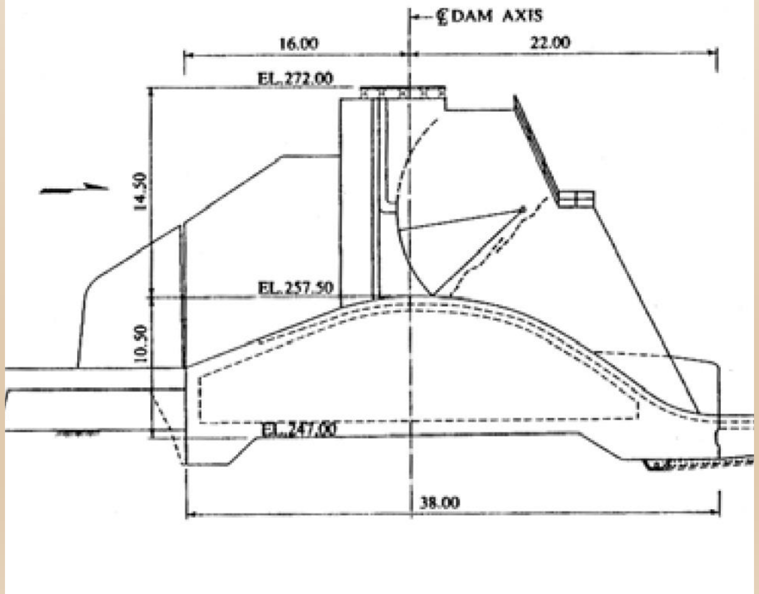


Figure 2.24. Cracks on Pier #1

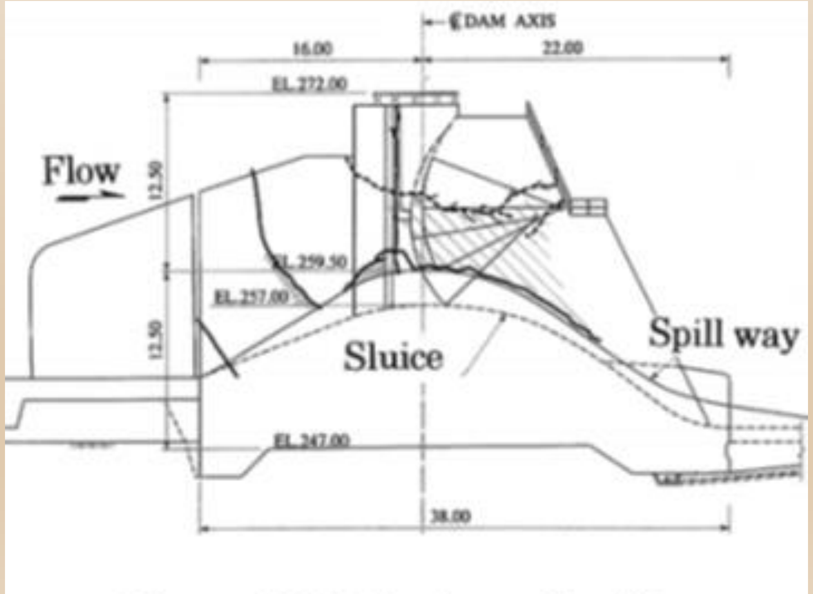


Figure 2.22. Cracks on Pier #2

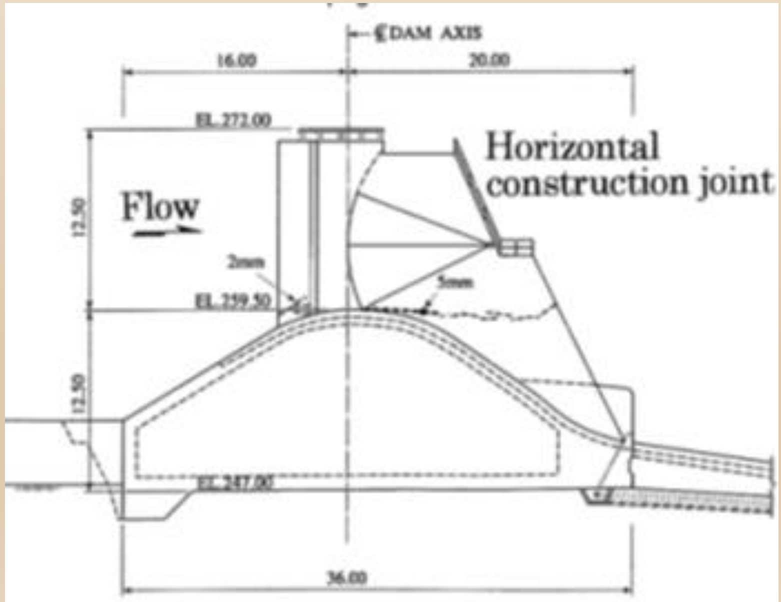


Figure 2.23. Cracks on Pier #3

Pier Exercise

- Concrete piers that are 5-feet thick and 40-feet high. Calculate the shear stresses at the base of the pier in the cross-canyon direction, for the 1000-, 5000-, 10,000-, and 50,000-year earthquake. Assume that the ultimate shear capacity of the spillway piers is 200 lb/in^2. Assume that there are no bridges that will load the pier. Estimate the probability that the cross-canyon shear capacity will be exceeded (provides information that would be used in middle of event tree for shear node).

Table V-6-4 - Spillway Pier Analysis – Earthquake Loads

Recurrence Interval, yr	Peak Horizontal Ground Acceleration
1000	0.2g
5,000	0.4g
10,000	0.5g
50,000	0.6g

Pier Exercise Solution

- The magnification factor for the pier is determined from Figure V-6-8, using the period of the structure and 2 %damping:
- **$T_s = FH^2/B$**

  Ts = 0.000643 x 1600/5 = 0.21
- Magnification factor for pier is 2.1.
- Magnification of PGA in CC direction assumed to be 1.5
- V = ½(150 lb/ft^2 + 315 lb/ft^2) x 40 = 9300 lb
- The shear stress at the base of the pier is calculated below:
- v = 9300/(60 x 12) = 13 lb/in^2

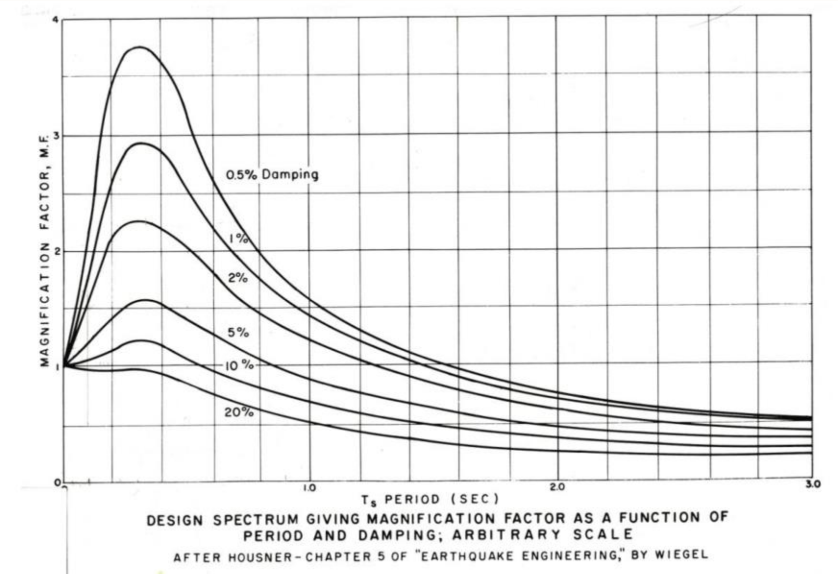
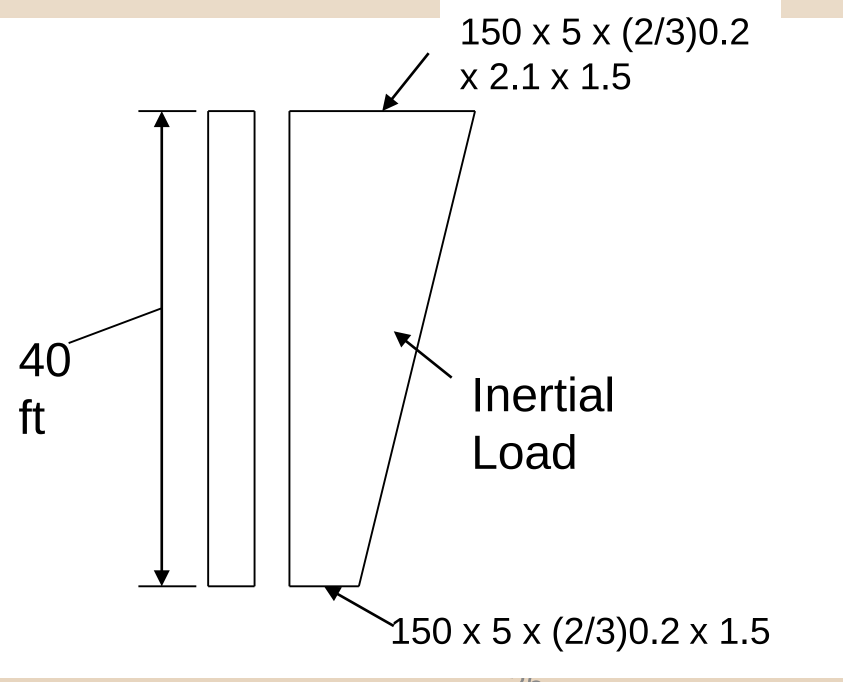


Figure V-6-8 – Magnification Factor for Seismic Pier Analysis (From Reclamation, 1971)



Shear Stresses at Base of Pier			
Recurrence Interval, yr	Peak Horizontal Ground Acceleration	Total Shear Force at Base of Pier	Shear Stress at Base of Pier
1000	0.2g	9300 lb	13 lb/in^2
5000	0.4g	18,600 lb	26 lb/in^2
10,000	0.5g	23,250 lb	33 lb/in^2
50,000	0.6g	27,900 lb	39 lb/in^2

Since the shear stresses are very low for all load cases and well below the stated shear capacity of 200 lb/in^2, the estimates for shear capacity being exceeded would all be very low (0.001).

NOTE: EXAMPLE ASSUMES NO POOL ON THE PIER. NO HYDROSTATIC OR HYDRODYNAMIC LOADING INCLUDED